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Influence of climate change on the frequency of daytime temperature inversions and stagnation events in the Po Valley: historical trend and future projections

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A B S T R A C T

This work analyzes the frequency of days characterized by daytime temperature inversion and air stagnation events in the Po valley area. The analysis is focused on both historical series and future projections under climate change. Historical sounding data from two different Italian stations are used as well as future projections data, provided by CMCC-CCLM 4-8-19 regional climate model (MED-CORDEX initiative). A new method to detect layers of temperature inversion is also presented. The developed method computes the occurrence of a temperature inversion layer for a given day at 12 UTC without a detailed knowledge of temperature vertical profile. This method was validated using sounding data and applied to the model projections, under two different emissions scenarios (RCP4.5 and RCP8.5). Under RCP4.5 intermediate emissions scenario, the occurrence of temperature inversions is projected to increase by 12 days/year (around + 10%) in the last decade of 21st century compared to 1986–2005 average. However, the increase in temperature inversions seems to be especially concentrated in the warm period. Under RCP8.5 extreme scenario, temperature inversions are still projected to increase, though to a lesser extent compared to RCP4.5 scenario (+6 days/year in the last decade of 21st century). A similar trend was found also for air stagnation events, which take into account the variation of precipitation pattern and wind strength. The expected increases are equal to +13 days/year and +11 days/year in the last decade of 21st century compared to 1986–2005 average, under RCP4.5 and RCP8.5 scenarios respectively.

1. Introduction

The Po Valley area is characterized by one of the highest population density in Europe as well as by one of the poorest air quality (EEA, 2014). Since the average emissions per capita are similar to other European urban areas (EEA, 2014), poor air quality is chiefly related to the adverse local climate (Carbone et al., 2010; Ferrero et al., 2011). As a matter of fact, the Po Valley basin is characterized by one of the lowest wind speed in Europe, on average between 2 and 2.5 m s^{-1}. During winter, the wind speed is even lower, around 1.5 m s^{-1} on average (Arpa Emilia-Romagna, 2013). Moreover, temperature inversions are very frequent, especially during the cold period when the height of Planetary Boundary Layer (PBL) rarely exceeds 450 m (Bigi et al., 2012). Temperature inversions reduce vertical dispersion ventilation into the free troposphere. Hence, primary pollutants tend to accumulate and secondary pollutants tend to form in a shallow layer near the surface (Perrino et al., 2014; Sandrini et al., 2014).

However, as climate is changing, a growing interest on the relationship between global warming and the diffusive properties of atmosphere has occurred over the last few years. According to Kirtman et al. (2013), the frequency of stagnation events will decrease on a global scale, although some increases are still possible in some regions. According to Horton et al. (2012), stagnation events are expected to increase by 12–25% by the end of 21st century in the Mediterranean area. Furthermore, climate change-induced variations of temperature and humidity can influence atmospheric chemical reactions and thus the formation of secondary pollutants (Stocker et al., 2013).

As regards Italy, some studies (Pasini and Cipolletti, 2007; Giulianelli et al., 2014) showed that global warming has already influenced atmospheric diffusive properties, although a clear trend cannot be detected due to the limited length of the assessment period. However, a 50% decrease of fog events, typically related to temperature inversions, has been observed in the Po Valley from the early 1990s (Giulianelli et al., 2014). This large decrease has been also found in other regions of the world, such as in California (Johnstone and Dawson, 2010). Potential causes of this trend might be the increasing temperature and the decline of available condensation nuclei due to the recent implementation of air quality policies focused on particulate matter emissions. However, since

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influence of climate change on atmospheric diffusive properties seems to be relevant to air quality issues, this work aims to analyze the historical trend and the projections for the frequency of diurnal temperature inversions and stagnation events in the Po Valley. Only daytime temperature inversions were considered in this work, because they usually correspond to particular conditions of atmospheric stability. Contrariwise, nighttime temperature inversions are typically due to the different solar radiation between day and night, and therefore they were not taken into account in this work.

2. Material and methods

2.1. Surface temperature

Data of surface temperature were acquired from 41 weather stations managed by four different Regional Environmental Protection Agency (ARPA) and from 7 weather stations managed by Aeronautica Militare (Fig. 1). Acquired data refer to the period 1985–2013.

These data show a statistically significant increase of surface temperature at a 5% significance level, in 90% of the considered stations. Averaging over the entire Po Valley basin, the estimated growth rate of surface temperature is equal to 0.55 K decade^{-1}.

2.2. Vertical profile of temperature

In order to compute the vertical profile of temperature, atmospheric temperature data were acquired from two weather stations, San Pietro Capofiume and Milano Linate. In the Po Valley basin, these two stations are the only ones where sounding data are collected. However, San Pietro Capofiume and Milano Linate can be considered representative of the so-called lower Po Valley and higher Po Valley respectively (Fig. 1).

San Pietro Capofiume station is managed by ARPA Emilia-Romagna. The main meteorological variables, namely atmospheric temperature, pressure, humidity and wind speed, have been monitored via radio-soundings since 1985. However, only measurements from 1987 to 2006 were analyzed in this work, because the number of valid data is >90% only during this period. Generally, observations are collected twice a day, at 00 UTC and 12 UTC (Universal Time Coordinated). For each observation, six paired measurements of pressure and temperature are available in the atmospheric layer between the surface and geopotential height at 850 hPa (on average).

Milano Linate station is managed by Aeronautica Militare. Sounding data at 12 UTC are available with a daily frequency during the period 1985–2012. On average, during the period 1985–1999, five paired measurements of pressure and temperature are available in the atmospheric layer between surface and geopotential height at 850 hPa (5.5 during winter). However, during the period from 1999 to 2012, the mean number of paired measurements increases to seven (eight during winter period), and therefore the estimated vertical profile of temperature becomes more accurate.

2.3. CMCC-CCLM4-8-19 model (MED-CORDEX initiative)

A regional climate model (CMCC-CCLM4-8-19) was used in order to assess the impact of climate change on the frequency of temperature inversions and stagnation events. This model, denominated just CMCC hereinafter, was developed by the Euro-Mediterranean Center on Climate Change within the MED-CORDEX initiative (www.medcordex.eu). The domain of this model is the entire Mediterranean area, partitioned into 6174 grid cells. Resolution of every cell is 0.44° × 0.44°, covering approximately a 50 × 50 km^2 surface (Ruti et al., 2011). The Po Valley area is situated within 17 cells, as shown in Fig. 2.

This model provides data both for the historical series (1950–2005) and for future projections (2006–2100), under different scenarios. It should be noted that the model runs on the past (1950–2005) have been performed without a specific initialization from a reanalysis. In this work, the 11 variables summarized in Table 1 have been considered.

Furthermore, two different RCP (Representative Concentration Pathways) scenarios were considered, namely RCP4.5 scenario and RCP8.5 scenario (Stocker et al., 2013; Van Oldenborgh et al., 2013). Every dataset has been downloaded from MED-CORDEX database (www.medcordex.eu).

2.4. Air stagnation index

The so-called stagnation events have been analyzed in this work as well as temperature inversions. A stagnation event is characterized by meteorological conditions that lack contaminant-scavenging capabilities and minimize the horizontal dispersion and vertical dispersion escape of pollutants (Wang and Angell, 1999). In the United States, air stagnation is monitored by the National Climatic Data Center (NCDC) via the air stagnation index (ASI). In the NCDC metric, stagnation events

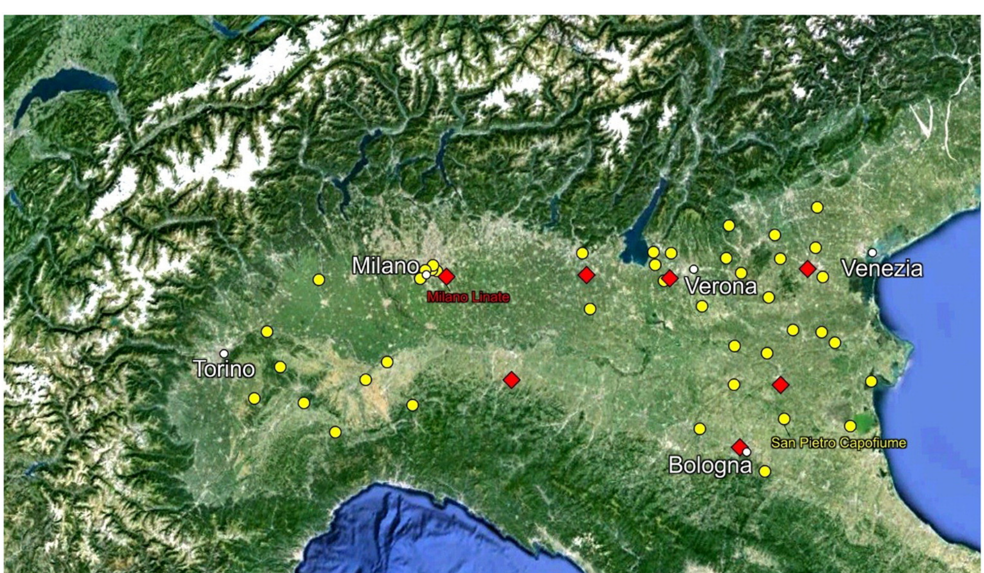

Fig. 1. Locations of ARPA weather stations (yellow circles) and Aeronautica Militare stations (red diamonds). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

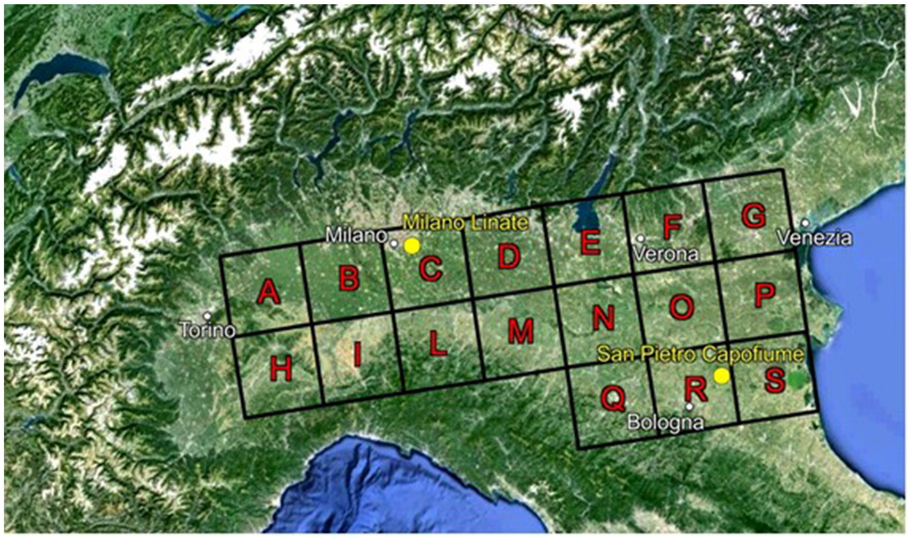

Fig. 2. Partition of the study area into the 17 cells of CMCC model. The total covered surface is 42,500 km^2.

are defined as periods with (i) light low level winds, indicative of a stable lower atmosphere with reduced horizontal dispersion and limited vertical dispersion escape, (ii) light upper level winds, generally associated with the establishment of persistent/slow moving warm core high pressure systems, and (iii) a lack of precipitation, minimizing the scavenging of airborne particulate matter (Horton et al., 2012).

Following the approach of Horton et al. (2012), a given day is considered to meet stagnation criteria when daily mean 500 hPa wind speed is <13 m s^{-1}, the daily mean 10 m wind speed is <4 m s^{-1} (4.4 m s^{-1} if the given day is characterized by temperature inversion), and the daily total precipitation is <1.0 mm (i.e., a dry day). If the value of any of the individual parameters is greater than the respective threshold, the given day is not characterized to be a stagnation event (Horton et al., 2012).

3. Estimation of temperature inversions frequency

3.1. Vertical profile of temperature from sounding data

For a given day, inversion layers between surface and geopotential height at 850 hPa can be easily detected from sounding data, calculating the temperature gradients with the following equation:

$$\left(\frac{dT}{dz}\right)_{i+1} = \frac{T_i - T_{i+1}}{z_i - z_{i+1}} \quad (1)$$

Where T_i and $T_{i+1}$are air temperatures at z_i and z_{i+1} altitudes respectively ($z_{i+1} > z_i$). On a typical day, i can take values from zero to five, where zero corresponds to the surface and five to 850 hPa pressure level. If the value of any of these temperature gradients is greater than zero, there is an inversion layer between the surface and the geopotential height at 850 hPa. If the first gradient ($i = 0$) is greater than zero, there is an inversion layer based at the ground level.

Analyzing sounding data from San Pietro Capofiume station, the frequency of temperature inversions between surface and geopotential height of 850 hPa can be assessed. As expected, the analysis showed that temperature inversions are more frequent during winter period. Moreover, on annual basis, the frequency of temperature inversions is on an upward trend (Fig. 3). Temperature inversions detected with this method will be denominated “observed data” hereinafter, since they are based on the observed vertical profile of temperature.

3.2. G850 gradient method

CMCC regional model provides only temperature data at surface and 850 hPa pressure level, with a daily frequency. Since an accurate vertical profile of temperature cannot be estimated using only these data, an alternative method has been developed to detect layers of temperature inversions.

Iacobellis et al. (2009) studied the variability of temperature inversions frequency in California. In their work, they simply used temperature gradient between surface and 850 hPa level pressure, denominated G850 (Eq. 2).

$$G850 = \frac{T_{850} - T_s}{z_{850} - z_s} \quad (2)$$

T_{850} and z_{850} are respectively temperature and geopotential height at 850 hPa level pressure, whereas T_s and z_s are respectively temperature and geopotential height at surface level. According to this method, there is a layer of temperature inversion if G850 is greater than zero.

However, this method applied to San Pietro Capofiume data highly underestimates the frequency of the observed temperature inversions. Moreover, the estimated trend is statistically different from the observed trend (Fig. 3).

The relevant underestimation can be explained by a more careful analysis of temperature gradients. As shown by the example in Fig. 4, a slightly negative G850 can actually “hide” a layer of temperature inversion: although G850 is equal to -0.56 K $(100\ m)^{-1}$, there is a very thick layer of temperature inversion (>400 m), between 600 m and 1100 m altitudes.

Table 1
Variables of CMCC model considered in this work.

Variable	Variable ID	Unit of measure
Daily mean near-surface air temperature	Tas	K
Daily mean air temperature at 850 hPa	ta850	K
Daily maximum near-surface air temperature	tasmax	K
Daily minimum near-surface air temperature	tasmin	K
Sea level pressure	psl	Pa
Geopotential height at 500 hPa	zg500	m
Precipitation	pr	kg $(m^2 \cdot s)^{-1}$
Eastward near-surface wind speed	uas	m s^{-1}
Eastward wind speed at 500 hPa	ua500	m s^{-1}
Northward near-surface wind speed	vas	m s^{-1}
Northward wind speed at 500 hPa	va500	m s^{-1}

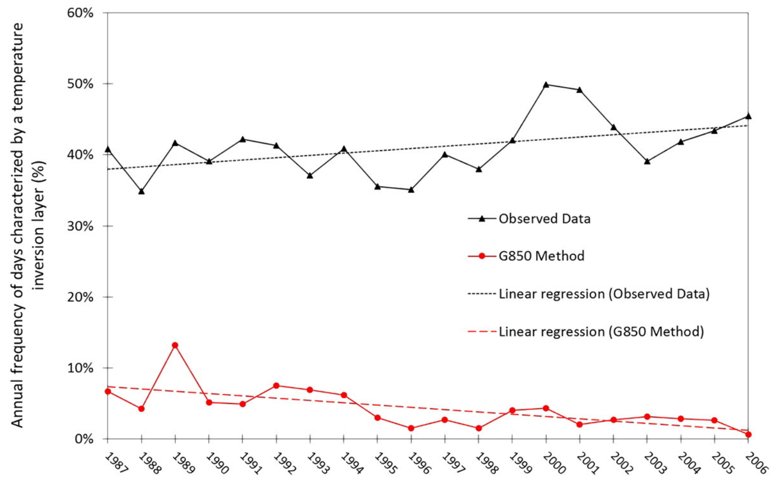

Fig. 3. Annual frequency of days characterized by temperature inversion at San Pietro Capofiume (12 UTC): comparison between observed data and G850 method over the 1987–2006 period.

3.3. The modified G850 method

Since G850 method cannot be successfully used to estimate temperature inversions frequency, a new method was developed to detect temperature inversion layers without an accurate knowledge of temperature vertical profile. Similarly to the G850 method, only variables available from CMCC regional model are used as input into this new method. This indirect method will be denominated Modified G850 method (ModG850) hereinafter.

In particular, a temperature inversion layer is detected if the following inequality is fulfilled:

$$G850>\beta \tag{3}$$

where β is a coefficient usually ranging between -0.4 K $(100\ \mathrm{m})^{-1}$ and -0.6 K $(100\ \mathrm{m})^{-1}$. The β coefficient is determined as a linear function of surface pressure *psl* (Eq. 4).

$$\beta(psl) = m \cdot psl + q \tag{4}$$

with both the parameters m and q to be estimated by calibration based on observed data. Hence, β coefficient can be computed using surface pressure as an explanatory variable, mainly because the higher the surface pressure, the higher the likelihood of a temperature inversion layer (Fig. 5).

The relationship between surface pressure and temperature inversions phenomena is physically based: subsidence inversions often occur in anticyclonic configurations, which are related to high-pressure systems.

Since anticyclones lead to higher absolute value of β coefficient, the detection of subsidence inversions is promoted in this situation, enhancing the accuracy of the *ModG850 method*.

The parameters m and q in Eq. 4 were estimated minimizing the errors between the observed inversions and the predicted inversions in San Pietro Capofiume station on a daily basis. Hence, this procedure maximizes the proportion correct (PC), i.e. the correct forecasts of both inversion and non-inversion events divided by the total number of valid days. The following results were obtained:

$$m = -\ 0.0677\ \mathrm{K} \cdot (100\ \mathrm{m} \cdot \mathrm{hPa})^{-1}$$

$$q = 6.29\ \mathrm{K} \cdot (100\ \mathrm{m})^{-1}.$$

It should be noted that the computed values of m and q are specific for the Po Valley area and for 12 UTC time.

The proportion correct of the developed method is 82.7% considering the entire valid dataset, and slightly higher considering just the

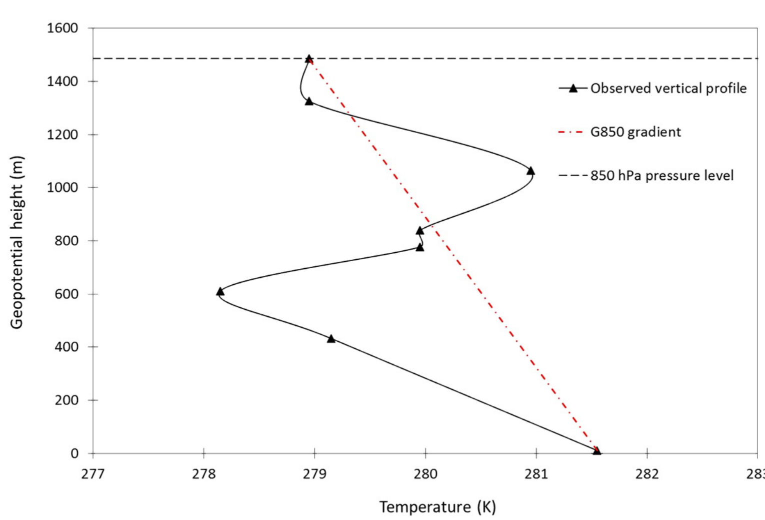

Fig. 4. Vertical profile of temperature observed at San Pietro Capofiume on 29/12/1987 (12 UTC).

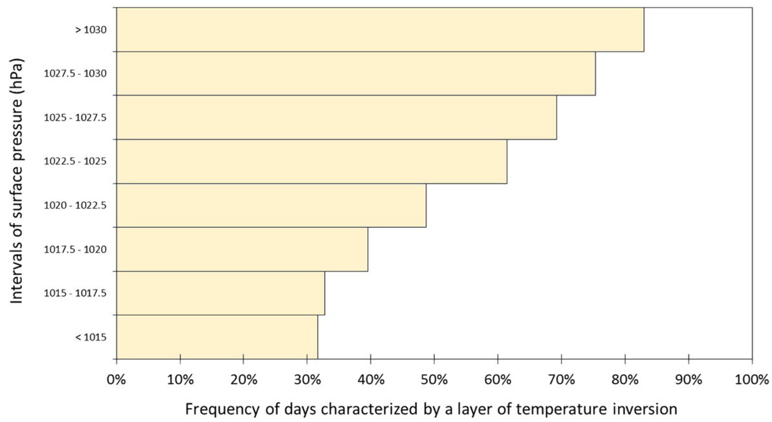

Fig. 5. Frequency of days characterized by a layer of temperature inversion for different intervals of surface pressure. Data refer to San Pietro Capofiume station during the period 1987–2006.

winter days (87.4%). Fig. SM1 shows the distribution of correct forecast days for a whole year (1992), which aims to represent a typical year in San Pietro Capofiume.

Finally, the goodness of fit of the *ModG850 method* on a larger scale was tested plotting the observed inversions against the inversions computed through Eq. 4 (Fig. SM2), on a monthly basis. Since the determination coefficient R^2 of the regression line fitted on this scatter plot is 0.97 relatively to the winter period (0.88 relatively to the whole year), it can be assumed that the *ModG850 method* explains accurately the observed inversions in San Pietro Capofiume.

3.4. ModG850 method validation

The *ModG850 method* was then validated using Milano Linate sounding data, which are available from 1985 to 2012 with a daily frequency, at 12 UTC. The number of days with valid observations during this period is 9614. For each of these days, the calibrated *ModG850 method* was applied to determine the occurrence of a temperature inversion layer. The proportion correct of ModG850 method applied to Milano Linate data is 79.1% considering the entire valid dataset (9614 days), and slightly lower considering just the winter days (77.9%). However, it should be noted that the two types of forecast errors (i.e. forecast of inversion in a non-inversion event and vice-versa) tend to compensate considering larger scales (e.g. monthly or annually), thus reproducing quite accurately the climate pattern of temperature inversions in Milano Linate station (Fig. 6).

The comparison between the modelled number of inversions and the observed number of inversions shows a good correlation. Again, the goodness of fit was tested plotting the observed inversions against the expected inversions, on a monthly basis. The determination coefficient of the regression line fitted on this scatter plot is 0.86 for both winter period and the whole year. Hence, the *ModG850 method* still explains quite accurately the observed inversions in Milano Linate.

However, the *ModG850 method* provides more accurate results after 1999, since the observed inversions before 1999 are affected by higher uncertainty (Fig. 6). As a matter of fact, the mean number of measurements in the atmospheric layer between the surface and 850 hPa pressure level is lower before 1999, leading to a less accurate estimate of vertical profile of temperature (Fig. 6).

Considering just the period between 1999 and 2012, the observed trend and the estimated trend do not show statistically significant differences at a 5% significant level. Moreover, the value of determination coefficient computed as before increases to 0.92 for the winter period and to 0.87 relatively to the whole calendar year.

3.5. Application of the ModG850 method to CMCC data

3.5.1. Assessment of 12 UTC temperatures

Since CMCC model provides only the mean daily temperatures whereas the *indirect method developed* is calibrated on 12 UTC data, a straightforward application of the *ModG850 method* to CMCC data is not possible. In order to make surface temperature data uniform, a

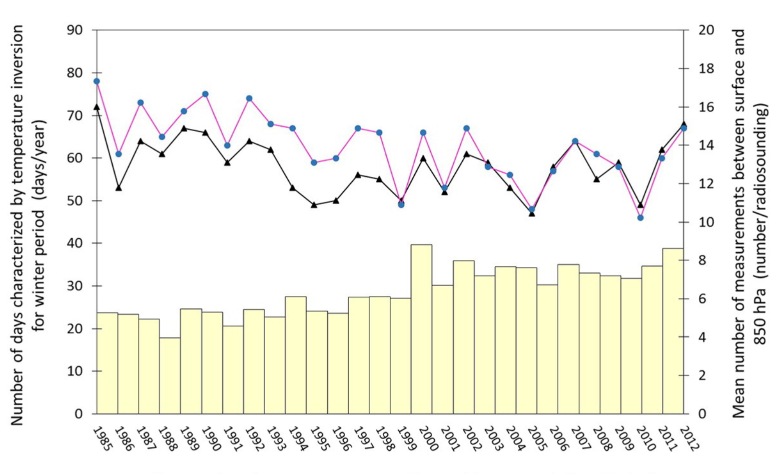

Fig. 6. Number of temperature inversions relative to winter period in Milano Linate (12 UTC): comparison between the observed temperature inversions and the estimated temperature inversions. Vertical bars represent the mean number of paired measurements of pressure and temperature between the surface and 850 hPa pressure level.

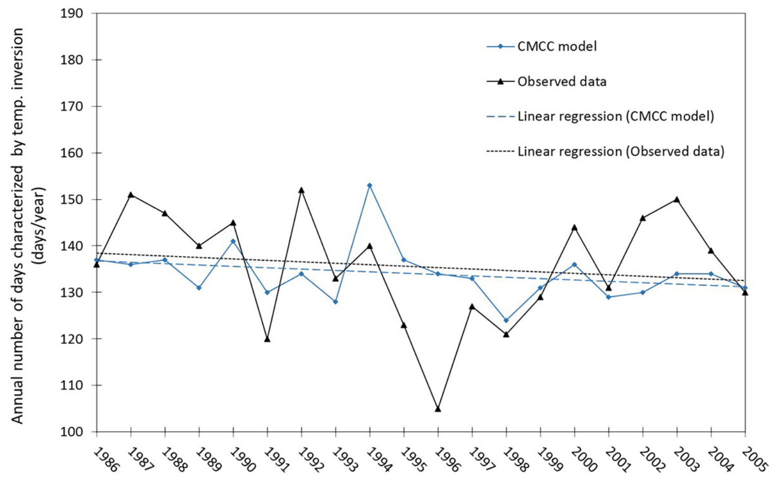

Fig. 7. Annual number of days characterized by temperature inversions in Milano Linate, relatively to the whole year: comparison between observed and estimated data.

model from De Wit et al. (1978) has been used. This model compute the surface temperature T_s at 12 UTC as a function of the maximum daily temperature (T_{max}), the minimum daily temperature (T_{min}) and the sunrise time (h_s) based on the following equation:

$$T_s\ (12UTC) = \frac{T_{max} + T_{min}}{2} - \frac{T_{max} - T_{min}}{2} \cdot\ cos\left(\pi \cdot \frac{12 - h_s}{14 - h_s}\right) \tag{5}$$

The goodness of fit of De Wit's model for the case study was verified using San Pietro Capofiume temperature data. In this station, both maximum and minimum daily temperatures are available, as well as temperatures at 12 UTC. The computed determination coefficient R^2 of this model is equal to 0.99, and therefore De Wit's model accurately estimates surface temperatures at 12 UTC.

However, CMCC model provides only maximum daily temperature and minimum daily temperature at surface. Hence, De Wit's model cannot be applied to estimate 850 hPa temperatures at 12 UTC. Nevertheless, the analysis of sounding data from Milano Linate station showed that the variation between 850 hPa mean daily temperature and 850 hPa temperature at 12 UTC is almost negligible. In particular, this analysis showed a good correlation between the single values of 850 hPa mean daily temperature and 850 hPa temperature at 12 UTC ($R^2 = 0.98$; Fig. SM3) as well as between the correspondent mean values, equal to 279.93 $\pm$ 6.01 K and 279.72 $\pm$ 6.04 K respectively (mean $\pm$ standard deviation).

Thus, the mean daily temperature at 850 hPa has been used directly in the application of the *ModG850 method* to CMCC data. It should be noticed that this assumption is coherent also from a physical point of view: the geopotential height at 850 hPa is comparable to the PBL altitude and therefore air temperature at 850 hPa is not really influenced by the solar radiation and by the day-night cycle.

3.5.2. Comparison between observed and estimated trends

The *ModG850 method* was applied to CMCC data from cell C (Fig. 2) to estimate the frequency of temperature inversions at Milano Linate, relatively to the period 1986–2005. This analysis aims to assess whether the *ModG850 method* applied to CMCC data can describe the observed trend of temperature inversions frequency. The comparison between these two trends is shown in Fig. 7.

Although there are some clear differences on the single annual values and even some anticorrelated years, the two trends tend to be parallel under a long-term analysis. Moreover, the two trends do not show statistically significant differences at a 5% significant level. The same kind of comparison about the winter period shows alike results (Figure SM4).

The differences in the single annual values are due to various sources of noise, such as the uncertainty of both ModG850 method and the

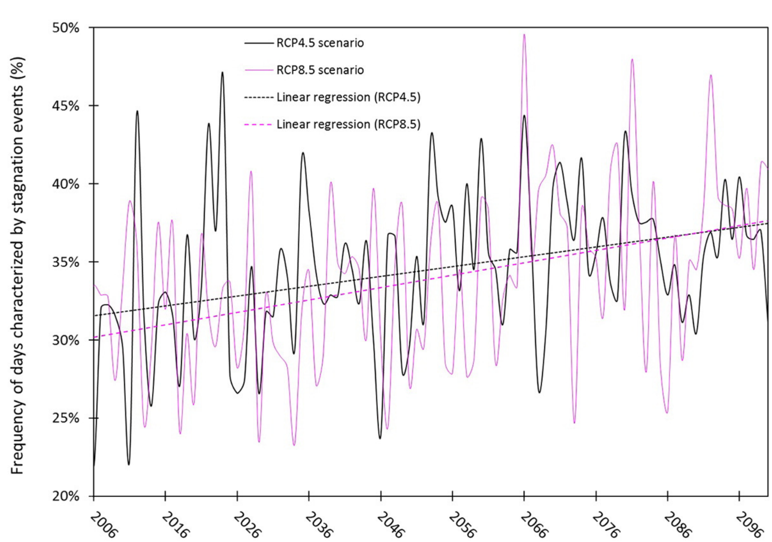

Fig. 8. Trend of annual frequency of days characterized by stagnation events, relatively to the whole year (days/year), estimated by CMCC model data.

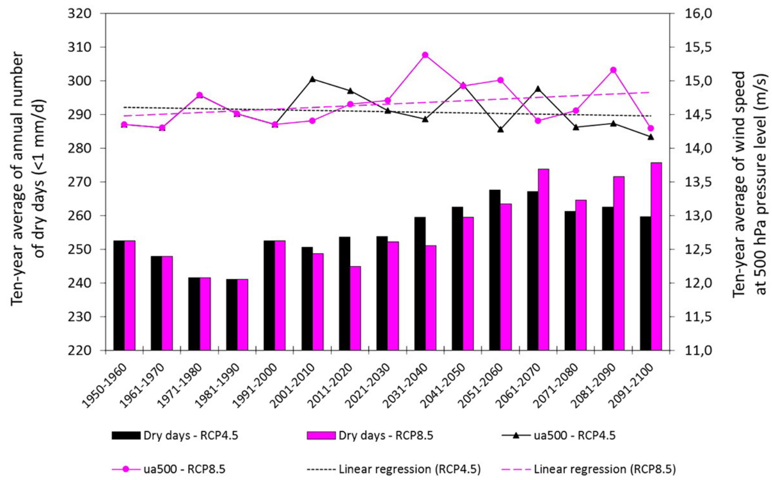

Fig. 9. Trend of the main variables related to stagnation events under both RCP4.5 and RCP8.5 scenarios.

climate model, since the historical runs of the model are not initialized from a reanalysis. Hence, it seems reasonable to assume that the ModG850 method applied to CMCC data can explain the historical trend and therefore can be used for future projections.

4. Future projections

4.1. Stagnation events

The dispersion of air pollutants in the near-surface layer of atmosphere is related to different characteristics of the atmosphere. In this work, two different phenomena have been analyzed, namely temperature inversions, related to the vertical profile of temperature, and stagnation events, related to wind speed and precipitation.

The annual frequencies of stagnation events for both historical (1950–2005) and future period (2006–2100) were computed using CMCC data, considering both RCP4.5 and RCP8.5 scenarios. On a daily basis, the occurrence of stagnation event was determined according to the literature criteria presented in Subsection 2.4. The results of this analysis for the entire Po Valley area are shown in Fig. 8. In accordance to Horton et al. (2012) studies - but unlike Wang and Angell studies (1999) - we did not set any length requirement on stagnation events (i.e. even a one-day event is considered a stagnation event) but we acknowledge that periods of persistent stagnation may have a different impact than an equal number of intermittently-spaced stagnation days (Horton et al., 2012).

Under both RCP4.5 and RCP8.5 future scenarios, the upward trends are statistically significant at a 5% significant level (Mann-Kendall test). The rates of increase are equal to +1.1 days decade^{-1} and +1.0 days decade^{-1} respectively. These upward trends are mainly due to the expected increase in dry days and the expected variation of wind speed at 500 hPa (under RCP4.5 scenario). Fig. 9 summarizes the predicted evolution of these two variables, highlighting why RCP8.5 rate of increase is slightly smaller than the RCP4.5 one. Indeed, under RCP8.5 scenario, wind speed at 500 hPa is expected to increase, promoting a higher pollution dispersal and therefore a reduction in stagnation event frequency. The greater increase in dry days under RCP8.5 scenario is therefore compensated by the increase of wind speed at 500 hPa.

4.2. Temperature inversions frequency

The annual frequencies of temperature inversions for both historical (1950–2005) and future period (2006–2100) were computed using CMCC data, considering both RCP4.5 and RCP8.5 scenarios. Fig. 10 shows the results of this analysis for the entire Po Valley area, relatively to the whole calendar year (period 2006–2100).

The application of the *ModG850 method* to CMCC data shows a statistically significant increase of temperature inversions frequency at a 5% significance level (non-parametric Mann-Kendall test) under both

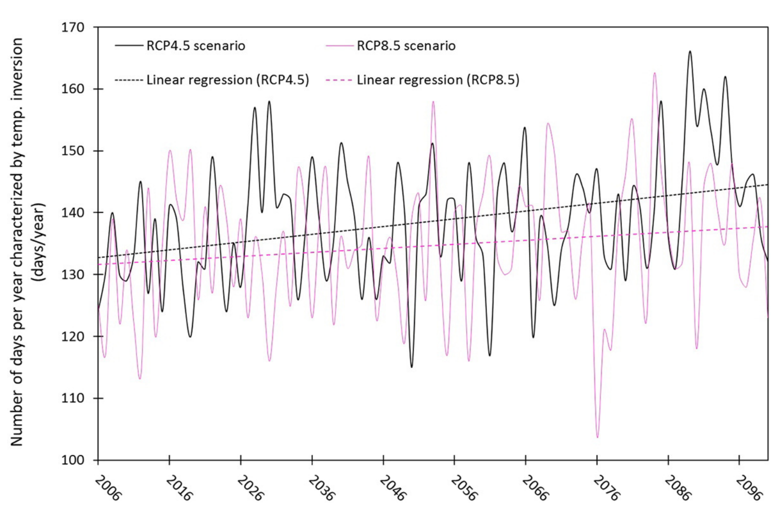

Fig. 10. Trend of annual number of days characterized by temperature inversion for the whole calendar year (days/year), estimated by CMCC data for the entire Po Valley basin.

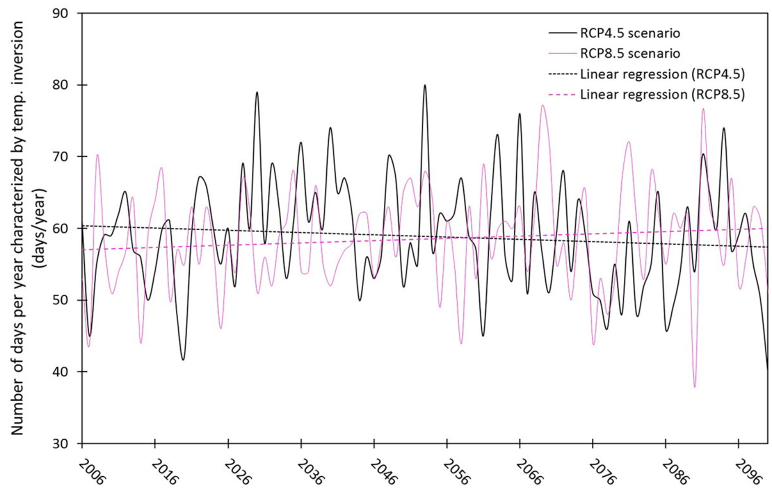

Fig. 11. Trend of annual number of days characterized by temperature inversion, relatively to the winter period (days/year), estimated by CMCC data for the entire Po Valley basin.

future scenarios. The rates of increase are +1.2 inversions/decade and +0.6 inversions/decade under RCP4.5 and RCP8.5 scenarios respectively. Therefore, under RCP4.5 scenario, the occurrence of temperature inversions is projected to increase by +12 days/year (around +10%) in the last decade of the 21st century compared to 1986–2005 average. On the other hand, the expected increase under RCP8.5 scenario is lower, being equal to +6 days/year in the last decade of the 21st century.

Under RCP8.5 scenario, the upward trend of temperature inversions is less accentuated compared to RCP4.5 scenario. As a matter of fact, under this more extreme scenario, the surface temperature is projected to increase more than the 850 hPa temperature, according to CMCC model. Hence, this different warming generates more instability in the near-surface layer of atmosphere, thus attenuating the trend of temperature inversions. This differential warming, predicted also under RCP4.5 scenario but at a lesser extent, is expected especially during winter period. In particular, the effect of this phenomenon is such that the trend of temperature inversions for winter period is almost stationary under both scenarios (Fig. 11).

From a physical standpoint, the upward trend of temperature inversions is due to the expected increase of anticyclonic periods. Temperature inversions are more frequent and more intense during these periods (Giuliacci et al., 2010), because of the descending movements of widespread layer of air masses, heated by compression. In turn, the expected increase of anticyclonic periods is due to the variation of general circulation of the atmosphere under global warming. The likely poleward expansion of Hadley cell (Lu et al., 2007; Kirtman et al., 2013) is mainly the reason why subtropical anticyclones will reach more frequently Po Valley latitudes, causing a greater persistence of such high-pressure systems. The expected increase in frequency of high-pressure systems in the Po Valley area is also confirmed by CMCC data, since anomalies of geopotential heights at 500 hPa show an upward trend (Figure SM5).

5. Conclusions

This work aimed to analyze the historical trend and the projections of both temperature inversions and stagnation events frequencies over the entire Po Valley basin. A new method was implemented to assess the projections of temperature inversions under climate change.

The developed method computes the occurrence of a temperature inversion layer for a given day at 12 UTC, using only four input variables (maximum and minimum daily temperature, 850 hPa temperature and surface pressure). This method was applied to CMCC model output, under two different emissions scenarios (RCP4.5 and RCP8.5).

Under RCP4.5 scenario, the mean annual surface temperature is expected to increase by 2.4 K in the last decade of the 21st century compared to 1986–2005 average. This increase will be associated to a small increase in temperature inversions frequency, by 12 days/year in the decade 2091–2100 compared to 1986–2005 average (around +10%). A similar trend was computed also for stagnation events, which take into account the variation of precipitation pattern and wind strength. Hence, the increased number of days per year characterized by stagnation events and temperature inversions will entail a potential negative impact on Po Valley air quality. However, the increase in temperature inversions seems to be especially concentrated in the warm period, although the seasonal analysis was not investigated extensively in this work. A future development of this work should be addressed to a more detailed seasonal analysis, for instance following the approach of Pasini and Cipolletti's studies (2007). Moreover, a further analysis on pressure fields could be performed to gain knowledge about the consequences on the stability of low atmospheric layers.

Under RCP8.5 scenario, surface temperature is projected to increase by 4.4 K in the end of 21st century compared to 1986–2005 average. Furthermore, both stagnation events and temperature inversions are also expected to increase, though to a lesser extent compared to RCP4.5 scenario, due to the increased air instability generated by higher temperatures. However, the general situation of air quality will be negatively affected by the lack of decarbonization of energy systems, which would be indispensable in a lower emissions scenario, such as RCP4.5 scenario. As a matter of fact, under the latter scenario, the reduction of primary pollutants emissions (>50%) would compensate the expected impacts on the diffusive properties of the near-surface layer of atmosphere.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.atmosres.2016.09.018.

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